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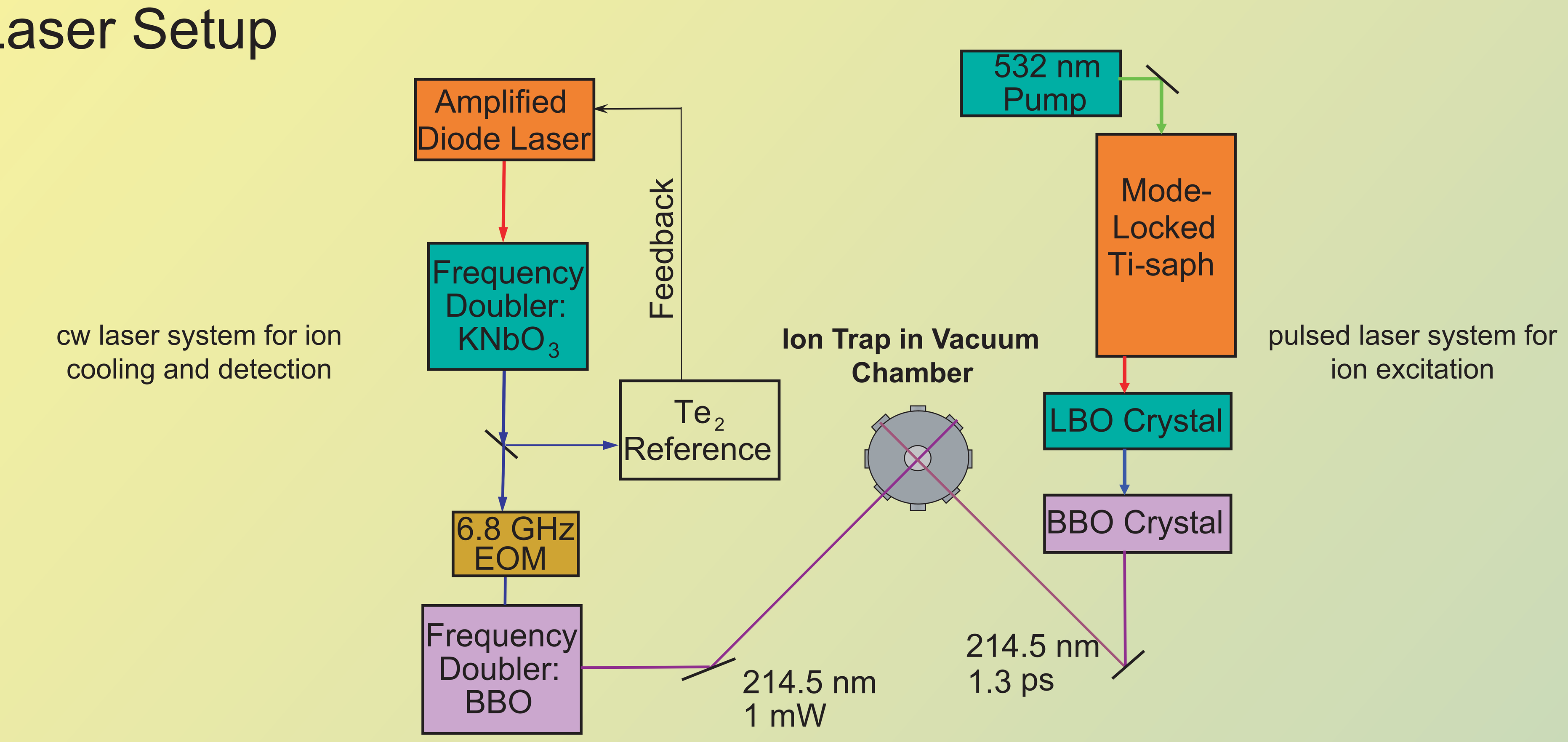
Two photon quantum interference of light emitted by two ions

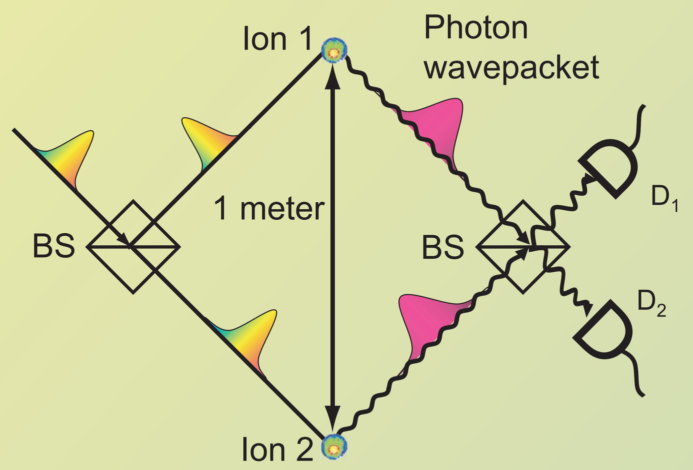
Goal: Multi-Ion (Probabilistic) Remote Entanglement

The remote probabilistic entanglement experiment will be run with two ions in two separate vacuum chambers. Joint photon detection heralds the entanglement of the two ions.

Laser Setup



Remote Entanglement Theory



The pulsed laser is split into two paths and then directed to each ion. Although the experiment looks like an optical interferometer, it has been shown that interferometric stability is not necessary for interference on the beamsplitter.

The complete quantum state before the beamsplitter of both entangled ion-photon pairs is:

$$|\Psi\rangle_{initial} = \left(|H\rangle_1|\uparrow\rangle_1 + |V\rangle_1|\downarrow\rangle_1\right) \otimes \left(|H\rangle_2|\uparrow\rangle_2 + |V\rangle_2|\downarrow\rangle_2\right)$$

When the photons are mode-matched on the beamsplitter, joint detection means that the photons were in an entangled state.

$$|\Psi\rangle_{photons} = |H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2$$

After detection of the photons, the quantum state of the ions has also collapsed into an entangled state. Because the entangled quantum state of the ions is long-lived, this entangled state can be used for subsequent quantum information processing.

$$|\Psi\rangle_{ions} = |\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2$$

The probability of a successful remote ion entanglement event is

$$p = \frac{P(detect)^2}{4} = \frac{0.002^2}{4} = 10^{-6}$$

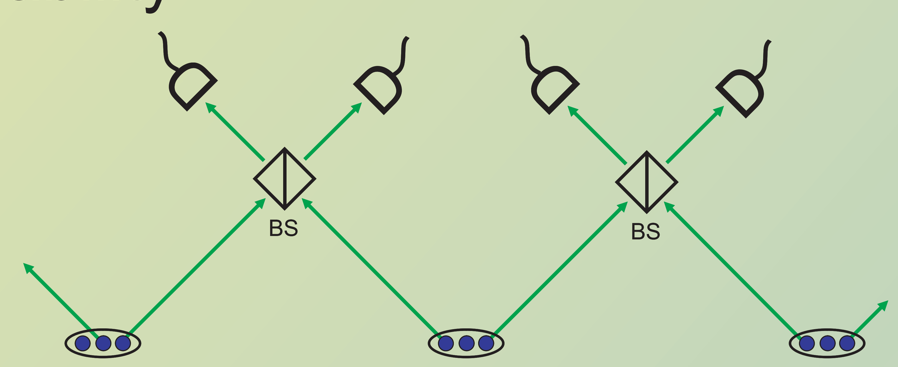
Only one Bell state detected

P(detect) = Single ion-photon entanglement probability

Rate= R*p~1 Hz

Simon and Irvine, PRL, **91**, 110405 (2003)

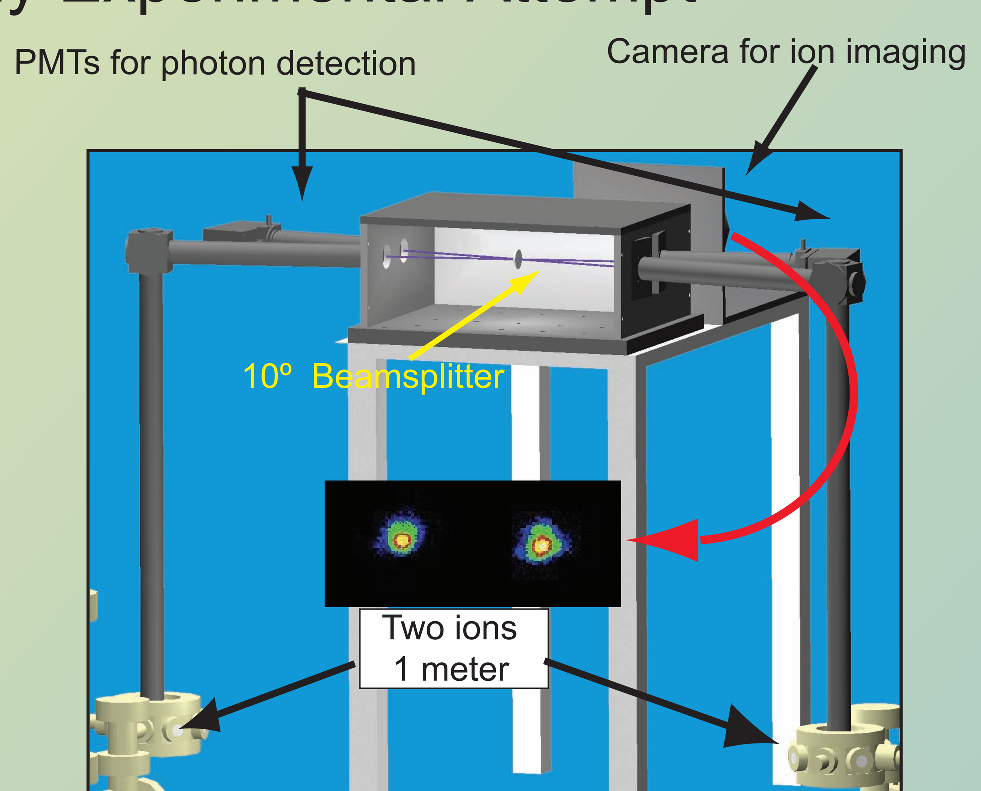
Scalability



Even though this entanglement is probabilistic, when combined with local deterministic quantum gates, this provides a possible method for scalable quantum computation.

Duan, *et al.*, QIP **4**, 165 (2004)

Early Experimental Attempt



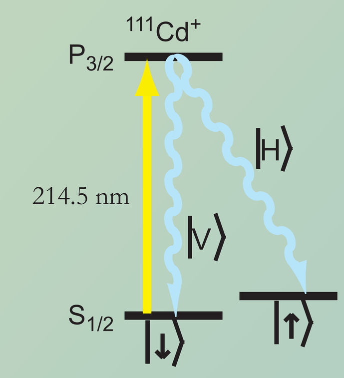
Schematic of the experimental setup showing the two vacuum chambers, each with a linear ion trap and photon collection optics. Inside a light-tight box was a 10° non-polarizing beamsplitter. After the beamsplitter, a mirror was inserted to image the ions simultaneously from both traps on a photon-counting camera. The inset is of two Cd ions, one in each vacuum chamber. Because the two images drifted independently on a 5 minute time scale and the spatial modes of the photonic qubits were not exactly the same, the mode-matching was insufficient to see photon interference.

Requirements

1) Ion-Photon Entanglement

We have shown probabilistic ion-photon entanglement in cadmium ions. The ion spontaneously decays via two channels with orthogonal polarization, leaving the combined ion-photon system in an entangled state prior to photon detection. The entanglement fidelity is >87% and is limited in part by multiple excitations of the ion by the weak cw pulse.

Blinov, *et al.*, *Nature*, **428**, 153 (2004),
Moehring, *et al.*, *PRL*, **93**, 090410 (2004)



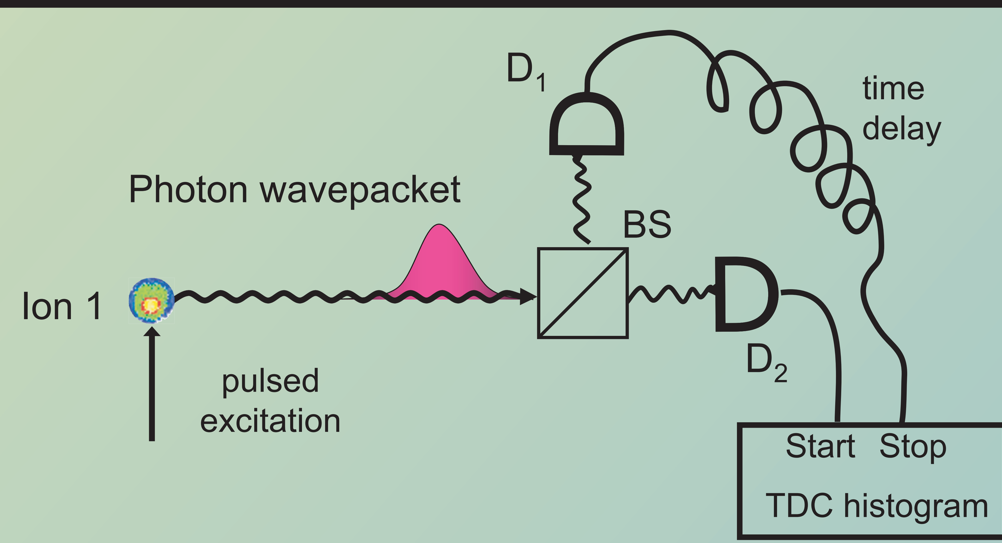
2) Single Photon Excitation

To eliminate multiple excitations from our weak cw pulse, we want to show a true single photon source from a pulsed laser excitation. We show data (below) that has a missing central peak with a contrast of better then 20:1, strong evidence for a single photon source in our cadmium ion.

3) Two Photon Interference - mode-matching

The free space coupling from two ion traps in two separate chambers was not successful due to thermal drifts and small differences in imaging optics. It appears necessary to send the ion light thorough a sufficient length of optical fiber to clean the photon mode for interference on the beamsplitter. However, UV fibers currently have an attenuation of 10dB/m @214 nm which is prohibitively large. We can however, show evidence of photon interference using two ions in the same trap. This eliminates some of the previously mentioned problems because both ions are imaged by the same optics and displacements are common mode.

Single Photon Excitation



Excitation with weak pulse

With a weak excitation pulse, it turns out that the rate of multiple excitations from a single ion is on the same order as the rate of simultaneous excitations from two ions:

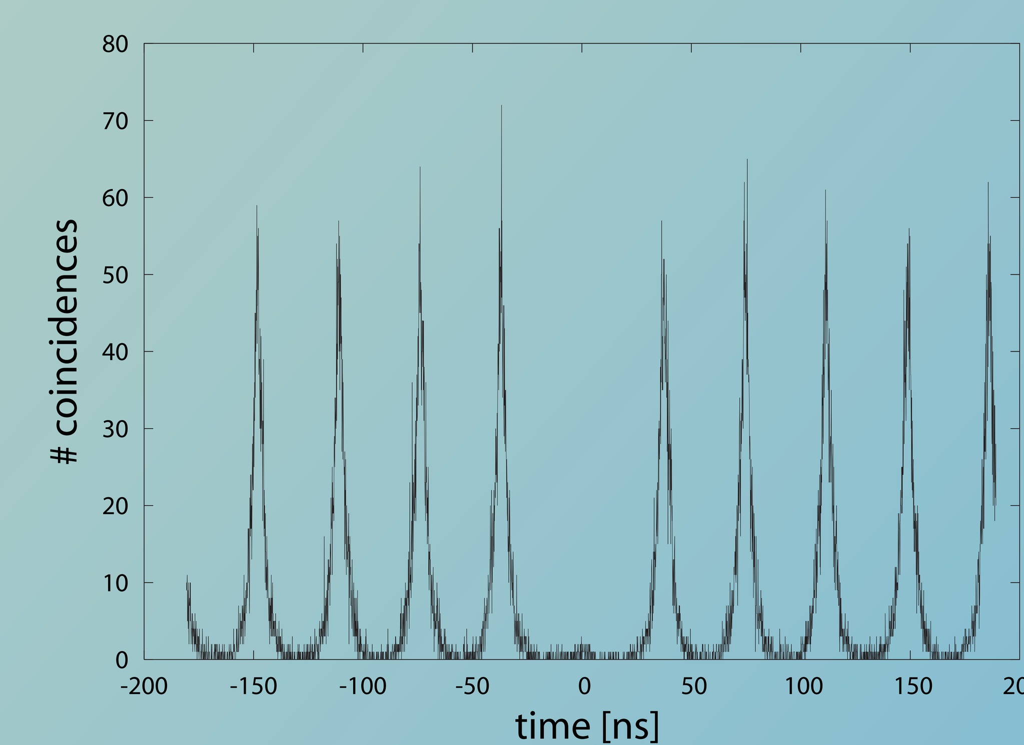
P_{exc}(single excitation, single atom) $= \rho$

P_{exc}(double excitation, single atom) $= \rho^2$

P_{exc}(single excitation, two atoms) $= \rho^2$

single excitation is necessary !

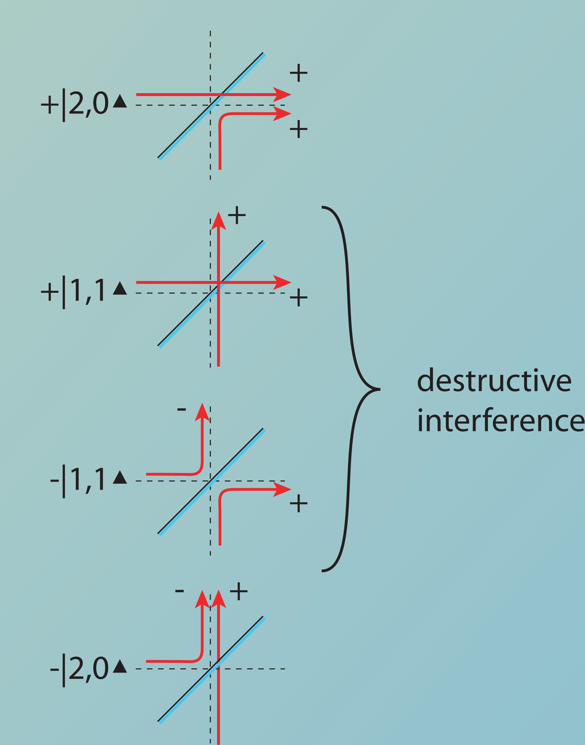
use mode-locked laser with pulse duration short compared to excited state lifetime



Autocorrelation $g^{(2)}$ of photons scattered by a single ion. The ion is excited by ultra-short pulses with a width of 1ps and a time distance of 37ns. Since the pulse duration is short compared to the excited state life time, at most one photon is emitted from each excitation pulse which is demonstrated by the near-perfect anti-bunching. The residual counts at zero delay are dominated by scatter of the excitation pulse itself.

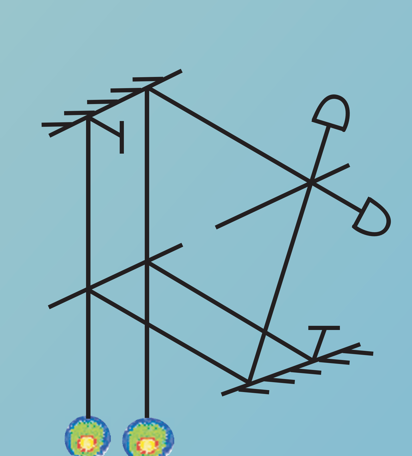
Two Photon Interference

One way to resolve mode-matching difficulty due to relative motion between ions is to have the ions located in the same trap. In this case, most of the motion is common mode.

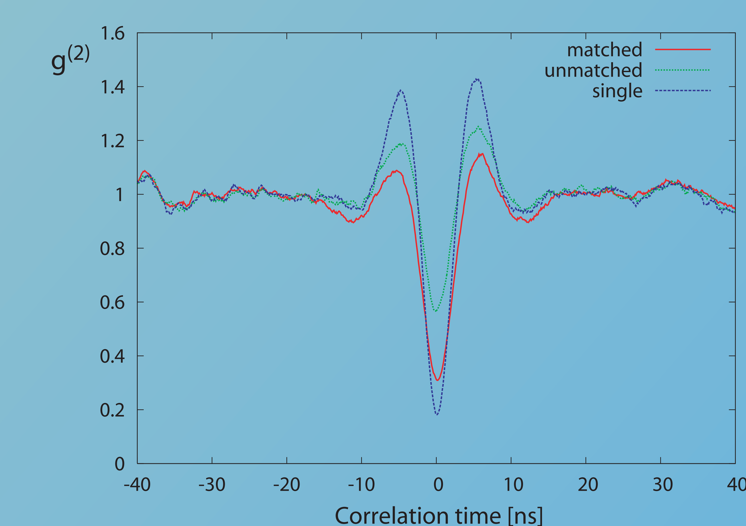


The different possibilities of two single photons impinging on a beam splitter can lead to interference. In particular, the two possibilities for observing one photon in each output port have opposite phase leading to destructive interference. As a consequence photon coincidences are never observed.
In order to observe this two photon or fourth order interference, no interferometric stability or phase relation of the incoming photons is necessary.

Hong, Ou, and Mandel, PRL, 59, 2044 (1997)



Schematic of the interferometer used to interfere two photons from two ions located in the same trap. The photons hit a beam splitter, one of two mirrors, and then are interfered on another beam splitter. One of the two possible paths for each ion is blocked so that the final beam splitter sees only the overlapping modes. Behind the beam splitter are two PMTs to detect the photons.



The three curves on this graph show an achieved mode overlap of approximately 60% by placing both ions in the same trap.
The curves show the autocorrelation $g^{(2)}$ of the detected photons. The lowest curve is taken with a single ion in the trap. For the highest curve the two paths are deliberately misaligned. In the case in which the two modes overlap (middle curve), fewer coincidences are observed compared to the misaligned configuration.

Compared to the case in which the ions are located in separate traps, we are now able to observe a signal of partial mode-matching because the motion of the ions is common mode, and the ions are both imaged by the same imaging system.